AIAA 96-0700

Small Spacecraft Telecommunications For The New Millennium's Technology Validation Missions

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Abstract

NASA's vision for science exploration in the next century is based on frequent, affordable missions enabled by small, low-mass, low-cost, highly autonomous spacecraft. Through the New Millennium Program (NMP), NASA is establishing a new and highly integrated approach to developing and flight-validating technologies that meet these spacecraft goals. Meeting the mission scenarios envisioned and the overarching goal of reducing lifecycle costs present significant challenges across all aspects of spacecraft design, implementation, and operation. This paper focuses on the advanced communication system architectures and technologies that have been identified by the NMP as key capability needs and are currently candidates for flight validation. These systems fall into three main categories: miniature deep space communications; extremely high bit rate, near-Earth communications; and short-range communications. Applications include: space-to-ground links, interspacecraft links for the relay of data between interplanetary spacecraft and associated landers and rovers, as well as near-Earth spacecraft communicating through crosslinks and data relay satellites. RF (400 MHz through 32 GHz) and optical communications technologies are discussed in terms of application and key performance parameters, e.g., mass, size, efficiency, and cost.

1. Introduction

A new era of space exploration is taking shape at NASA. This era is best characterized by frequent, affordable missions enabled by small, low-mass, low-cost, highly autonomous spacecraft. Such a departure from the past necessitates re-thinking the science aspects of a mission, as well as the enabling space and ground systems. NASA has set in place a technology validation program, the New Millennium Program (NMP), aimed at accelerating the identification, development, and flight validation of new and emerging spacecraft systems that can meet these new mission goals. The advanced technology component of the NMP is organized into several thrusts, addressing such areas as: autonomy, structures, and microelectronics. The products of these thrusts will then be validated through a series of NMP flights during the latter half of this decade. Of interest in this paper are the advanced communication system architectures and technologies that have been identified by the NMP as key capability needs. Figure 1.1 depicts several of the communication scenarios considered.

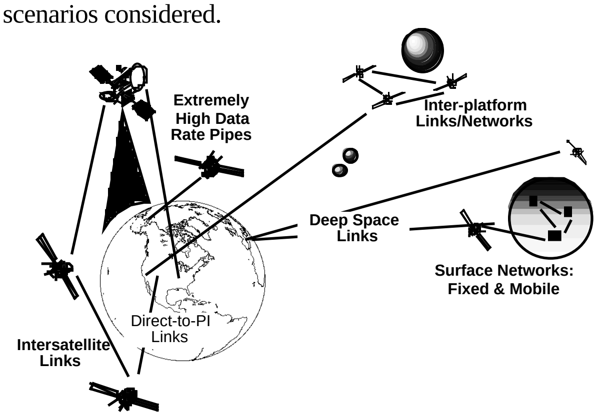

Figure 1.1 Space Communication Links

Working in conjunction with the near-Earth and deep space science communities, the following specific high-level communications needs were established early in the NMP:

- Miniature deep space communications
- Extremely high bandwidth near-Earth communications
- Direct-to-PI near-Earth communications
- Constellation communications

From these needs a list of high priority technologies was developed:

- Ka-band telecom components
- High data rate RF transmitters
- Optical communications systems
- Short-range, low bit rate telecom chip sets
- Low mass, low power integrated electronics

Significant in this list is the presence of higher frequency band systems that represent a major shift in NASA's space communications frequencies. This shift is brought about, in part, by the advantages of shorter wavelengths, as well as recognition of the present and anticipated pressures on NASA to move to higher bands. Also noteworthy in this list is the emergence of short-range, low bit rate communications, which contrasts sharply with NASA's traditional point-to-point links. The space exploration vision for the 21st century calls for chip-level telecom systems that link together such missions as: constellations of spacecraft; virtual instruments composed of multiple spacecraft; surface planetary networks of fixed and mobile platforms; and planet surface to relay orbiter. These links typically support 10's to 100's kbps over distances in the range of 1000 km to less than 1 km, and operate in the UHF band (~400 MHz), although S-band (2-3 GHz) is a possible candidate.

Implicit in all of the above are the overarching goals of reduced-mass systems and lower mission lifecycle costs.

With this technology framework in place, a Communications Systems Integrated Product Development Team (IPDT) was established to meet the aforementioned set of goals. Through a competitive process, a team of industry/academia representatives was selected to work with a small group of NASA engineers. This paper outlines the breakthrough technologies and their applications, as identified by this IPDT for development and flight validation. The material is organized as follows. Section 2 of the paper deals with new and emerging technologies in deep space and near-Earth RF communications. Section 3 is similarly focused on deep space and near-Earth, but from the perspective optical communications. Section 4 completes the technology overview with a description of short-range, low bit rate communications; concluding remarks are given in Section 5.

2. RF Communications

The major NASA space communications frequencies presently cover S- (2 GHz) through Ku-band (14 GHz). As mentioned above, the NMP is planning to develop and demonstrate technologies at Ka-band, 20-27 GHz for near-Earth and 32 GHz for deep space.

There is also much synergy between the deep space and near-Earth technologies, particularly where miniaturization through high levels of integration and low cost implementations are concerned.

2.1 Deep Space

Miniaturization of the spacecraft communications payload and the introduction of Ka-band operational links are the major thrusts in this area. The vision for the small spacecraft telecom payload is a highly integrated radio frequency subsystem that exploits recent advances in electronics devices and packaging, digital signal processing, and materials. These advances, along with new approaches to antenna design, will have a significant impact on the power, mass, volume, and cost of the telecom payload. Figure 2.1.1 illustrates a simplified telecom block diagram for a deep space spacecraft; the dotted line in this figure indicates the option for coherence between the receive and transmit paths. The Ultra-Stable Oscillator shown is used to meet the high stability requirements of science experiments that make dual use of the radio signals.

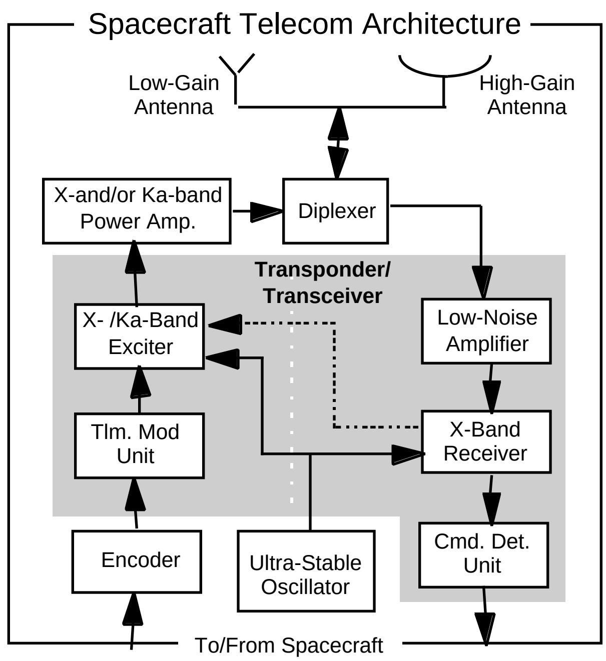

Figure 2.1.1 Simplified Spacecraft Telecom Architecture

Ka-band links offer a significant telecom advantage over X-band (8.4 GHz) because the higher frequency allows the spacecraft to focus RF energy into a smaller beam. For the same antenna size and RF output power, the advantage approaches the square of the ratio of the frequencies, i.e., ~12 dB. The adverse effects of system inefficiencies, propagation, receiver noise temperature and antenna pointing accuracy, reduce this advantage to 6 - 8 dB. A communications link design can utilize this advantage in either lower transmit power at Ka-band or smaller spacecraft antenna aperture. For example, today a typical spacecraft with a 1.5 meter diameter antenna and a 13 W X-band transmitter would sustain 122 kbps over a distance of 1 AU (148 x 10^6 km) to Earth. For the same spacecraft operating at Ka-band, but with a lower power transmitter, e.g., 3 W, 100 kbps could be achieved over the same distance. The ground segment assumed for this example is the new 34-m beam waveguide antennas[1] that have been recently deployed at NASA's Deep Space Network facility in California. The net Ka-band advantage for this example is ~ 5.5 dB.

Central to realizing this vision is a highly miniaturized deep space transponder/transceiver (see Figure 2.1.1) that is revolutionary in nature through the use of innovative digital signal processing techniques and application specific integrated circuits (ASICs) to perform functions traditionally realized in analog circuitry. This NMP-proposed transponder, the Deep Space Tiny Transponder (DSTT), offers an order-of-magnitude reduction in volume and mass, and almost a similar reduction in cost, when compared to the Cassini spacecraft transponder, which represents the current standard for deep space missions.

A comparison is shown graphically of key transponder metrics in Figure 2.1.2 among the Cassini spacecraft transponder; the Small Deep Space Transponder (SDST), which is currently under development by industry for NASA; and the NMP-proposed DSTT. Both the DSTT and SDST are designed to be functionally equivalent to the Cassini transponder, and, additionally, have Ka-band exciters. The conceptual layout for the DSTT is presented in Figure 2.1.3.

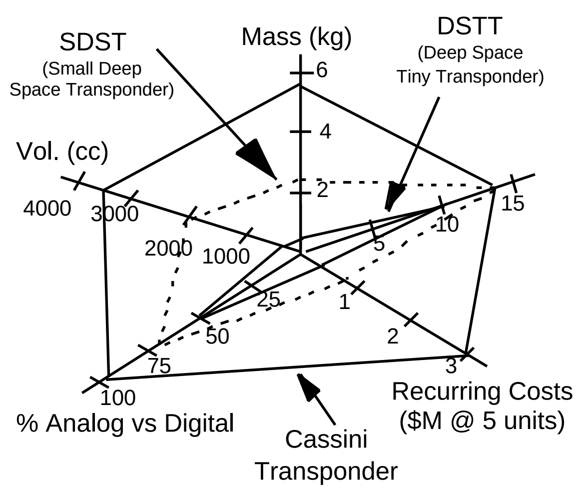

Figure 2.1.2 Deep Space Transponder Comparisons: Expected Performance Improvements

The development of small, highly efficient power amplifiers is also critical, since they typically place the biggest telecom demand on the spacecraft DC power source. For the power ranges considered by the NMP

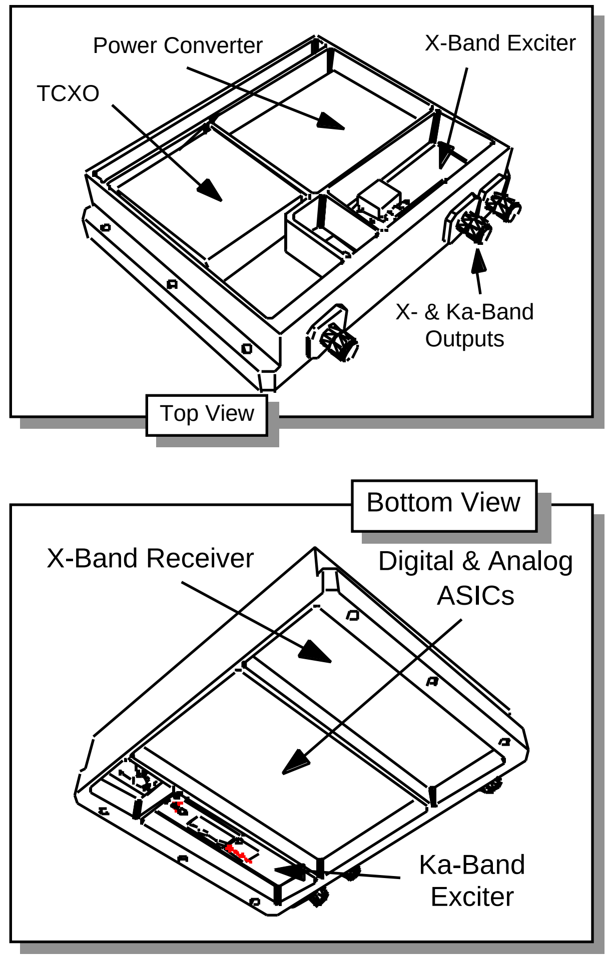

Figure 2.1.3 Proposed Layout of the Deep Space Tiny Transponder (10.5 x 8 x 3.5 cm)

(< 5 W for Ka-band, <15 W for X-band), solid-state power amplifiers (SSPAs) appear to offer the best solution in terms of watts/kg and power added efficiency (PAE). Traveling wave tube amplifiers (TWTAs) and microwave power modules (MPM), a hybrid TWT/SSPA arrangement, discussed in Section 2.2, are more suited to higher power levels.

While the Ka-band SSPAs are less mature, the trend, shown in Figure 2.1.4, is for increasingly efficient SSPAs, approaching X-band efficiencies. This is achievable using the latest device technology, such as pseudomorphic high electron mobility transistors (PHEMTs).

The key remaining telecom component is the spacecraft high gain antenna: the major mass driver for a small spacecraft telecom payload. Despite the wavelength advantages discussed above, apertures diameters on the order of 1.5 m are still required to establish deep space links at the desired data rates, ~100 kbps at 1 AU. For the first NMP flight, a lightweight composite material, solid parabolic antenna has been proposed with a dual X-/Ka-band feed. This antenna offers a x2 mass reduction over previously flown antennas (see Figure 2.1.5), while providing the high surface accuracy necessary for Ka-band operation.

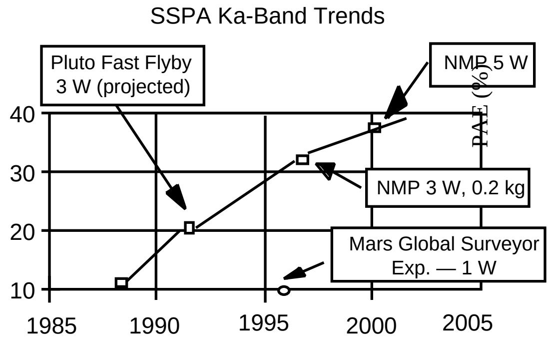

Figure 2.1.4 SSPA Ka-band Efficiency vs. Time

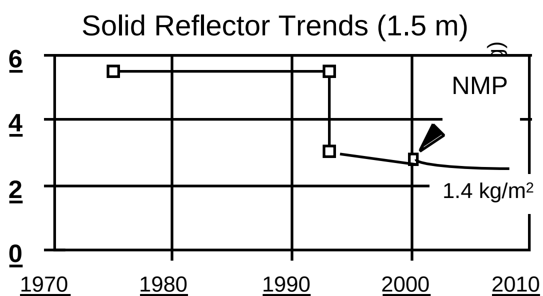

Figure 2.1.5 Deep Space Antenna Mass vs. Time

For later NMP flights, more aggressive concepts are under consideration that emphasize stowed antenna volume vs. deployed, and further reductions in mass. One concept under development is an inflatable reflector, with a deployable feed, that could potentially offer a deployed-to-stowed volume ratio of ~10, with comparable mass to the solid parabolic antenna at 2-m. Other deployable antenna candidates include flat and ultra-lightweight, “fishnet” reflectarrays. The latter antenna uses chords to suspend radiating elements, which, in principle, can achieve very low mass-to-aperture ratios (0.6-1.0 kg/m^2).

2.2 Near-Earth

Flexible technology options are the key to providing communications services for near-Earth missions of the 21st century. Use of existing communications infrastructure in ground stations and relay satellites for S, X, and Ku bands will be combined with new capabilities in Ka-band using standardized components to yield the most cost effective means to accomplish the science mission. Figure 2.2.1 illustrates the variety of communications links which may be used.

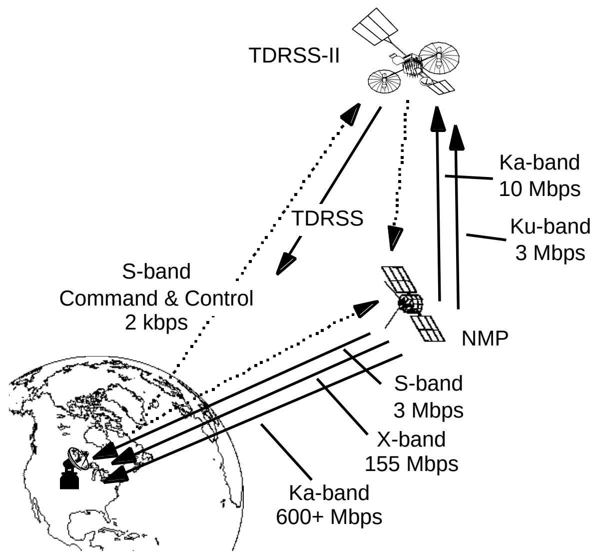

Figure 2.2.1 Near-Earth Communications Options

The science instruments flown by the NMP will require the return to Earth of increasingly large science data volumes, using communications equipment that is lighter and more power efficient, operates autonomously, and supports lower cost ground facilities, spacecraft operations, and data processing.

To achieve lower costs in operating these next generation spacecraft, command and housekeeping communications will be increasingly demand-driven and asynchronous. The NASA 4th generation transponder system is being developed by industry to satisfy these requirements, while maintaining compatibility with the existing NASA S-band infrastructure. Communications direct to Earth or via the Tracking and Data Relay Satellite System (TDRSS) can be accomplished either by fixed schedule, as is currently done, or initiated independently by either the ground or the spacecraft. Small, low-cost, omni-directional antennas are used, with data rates varying from as low as 128 bits/second up to 2 megabits/second. This technology is proposed as the standard for flight on all NMP near-Earth missions. Figure 2.2.2 shows the improvement that can be achieved with this technology in several key metrics compared to a transponder which is currently flown on NASA in missions (Figure 2.2.3).

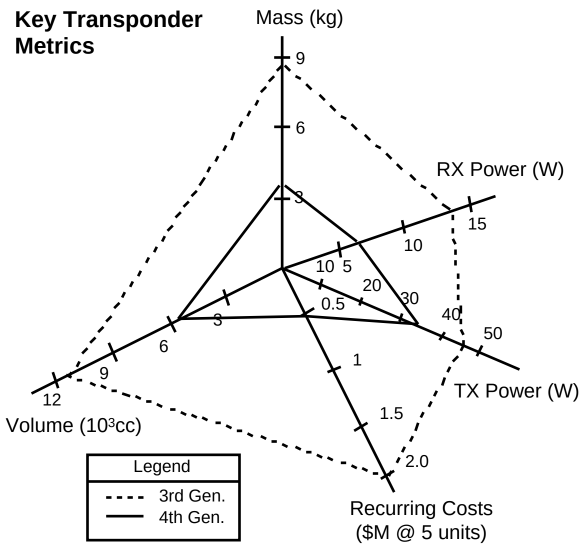

Figure 2.2.2 Expected Improvement in Key Metrics of the NASA Standard S-band Transponder

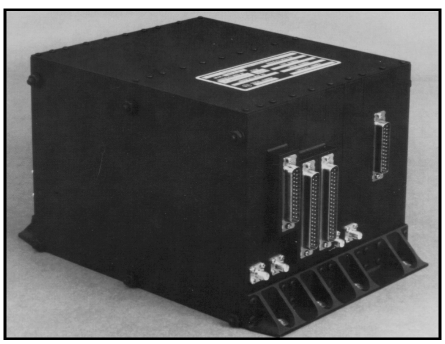

Figure 2.2.3 NASA 3rd Generation Transponder

In addition to the relatively low-rate command and control communications described above, transfer of multi-terabit daily data streams of science data to central archives for programs such as the EOS will be required. It is also anticipated that increasing numbers of end users such as universities will desire direct access to spacecraft instruments using low-cost ground stations. These operations will require peak data rates of tens to hundreds of megabits/second and must be accomplished with high-gain onboard antennas of a size dictated by the small dimensions of the New Millennium spacecraft. These size restrictions and the increasing international competition for RF spectrum will ultimately force all users to utilize current allocations more efficiently and develop the technology to use new frequencies such as Ka-band (20-27 GHz). This band is desirable in that it provides both wider frequency allocations for higher downlink rates and smaller antennas for a given gain due to its shorter RF wavelengths.

Phased array antennas with integral, distributed RF power amplifiers are seen as a solution to the problems associated with providing high gain for science downlinks without the deployable structures, moving parts and torque disturbances that are associated with current mechanically steered high-gain antennas. An interim, X-band antenna capable of supporting 155.52 Mbps to a 6-m class ground station has been proposed for the first NMP near-Earth mission with a follow-on Ka-band unit capable of 622 Mbps to a ground station of similar antenna size. Figure 2.2.4 indicates the improvement in performance that can be achieved with the X-band system compared with NASA's Landsat-7 system, which will have similar performance. Figure 2.2.5 illustrates the architecture of the phased array.

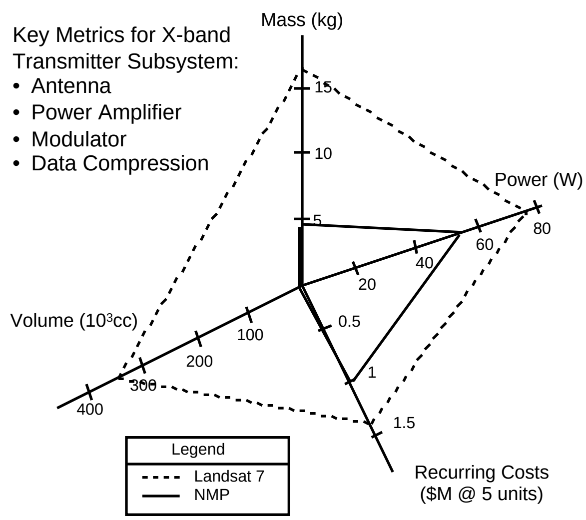

Figure 2.2.4 Expected Improvement in Key Metrics of the X-band High Data Rate Transmitter

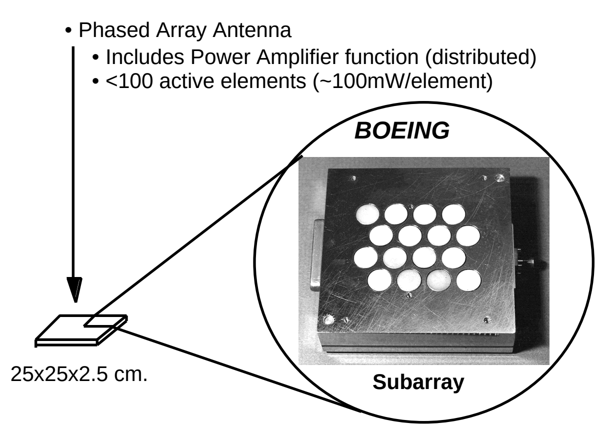

Figure 2.2.5 Phased Array Antenna System

NASA GSFC and LeRC have each been actively involved in the area of high data rate modulation and coding techniques. In particular, LeRC has developed, in cooperation with industry, a low cost, reconfigurable digital encoder/modulator (Figure 2.2.6) for medium to high data rate communications links.

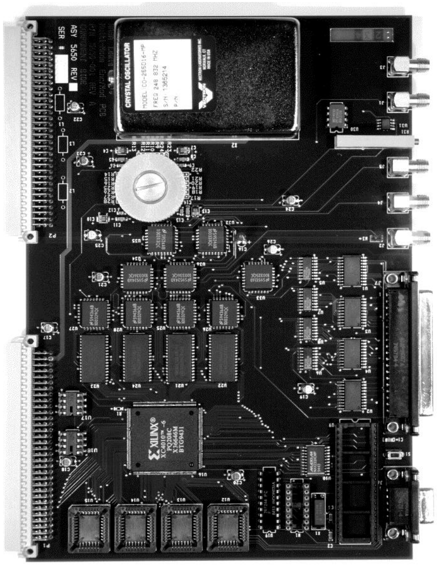

Figure 2.2.6 LeRC Encoder/Modulator Brassboard

A baseline prototype has been fabricated for 155.52 Mbps operation in a standard 72 MHz commercial transponder channel. A concatenated coding scheme consisting of a Reed Solomon (255,239) outer code and a pragmatic rate 5/6, four dimensional trellis inner code has been designed specifically for 8-ary modulation formats. The scheme requires about 7.8 dB E_b/N_o for a bit-error rate of 10^{-12} and offers bandwidth efficiencies greater than 2 bps/Hz. The unit is programmable and reconfigurable to support a wide range of data rate requirements, especially those requiring large data return, i.e., high-resolution remote sensing instruments.

Among the latest advancements in high-power RF amplifiers is the microwave power module (MPM, Figure 2.2.7). The MPM consists of a short TWT with a solid-state MMIC driver section. Present commercially available versions operate from 6-18 GHz, with RF output power levels to 100 W. The need for space-qualification and development of a lower mass, electronic power conditioner (EPC) are two areas which are being targeted within the NMP, which is considering the MPM for possible deep space and near-Earth applications at X-band and Ka-band.

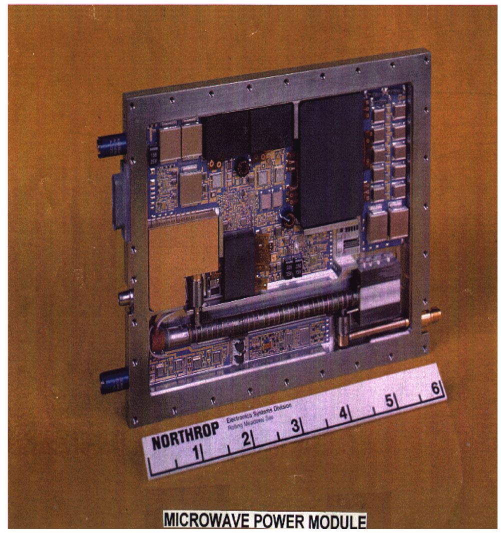

Figure 2.2.7 Microwave Power Module

3. Optical Communications

Through the NMP, NASA has the opportunity to flight validate optical (laser) communications. Optical communications systems offer three key advantages over RF systems, as a result of the very short optical wavelength (¬), 1µm vs. 1 cm (Ka-band). The advantages are: 1) the reduced size of communications payload, 2) aperture gain, or directivity, which scales with 1/¬^{2}, and 3) the virtually unlimited, and currently unregulated, bandwidth.

Because of the very high directivity of the optical beam, significant increases in link capacity (x10 - x100) can be achieved over Ka-band communications, while minimizing the power, mass, and size burden on the spacecraft. The typical large parabolic antennas of current spacecraft will be replaced by telescope apertures in the centimeter class, which will be integrated with the tracking and detection electronics.

3.1 Deep Space

NASA has in place space and ground optical technology development programs at the Jet Propulsion Laboratory (JPL), which have a significant deep space focus. At the core of the NASA spacecraft technology development is the Optical Communications Demonstrator (OCD) program.[2] This program is developing an engineering model of a flight terminal capable of returning kbps to Mbps from the planets, or Gbps from high-Earth-orbit to the ground (see Section 3.2). The system uses a “minimum-complexity” architecture that uses only one detector array and one fine steering mirror to accomplish beacon signal acquisition, tracking, transmit beam pointing, and transmit/receive coalignment (with point-ahead to accommodate cross velocity). Tracking of the beacon signal is accomplished by using a windowed sub-frame readout from the detector array.

The system consists of a single transmit/receive telescope (shown in Figure 3.1.1), a fiber-optic coupled transmit laser assembly, and a separate control processor. All of the optics are located in the telescope assembly. A coarse pointing gimbal assembly is not needed except in mission applications where separate pointing of the terminal relative to the spacecraft is required. The telescope aperture size is 10 cm and the transmit source is a 1-W, diode-pumped, solid-state laser. Such a system can deliver 500 kbps from 1 AU to a 10-m "photon bucket" optical receiver.

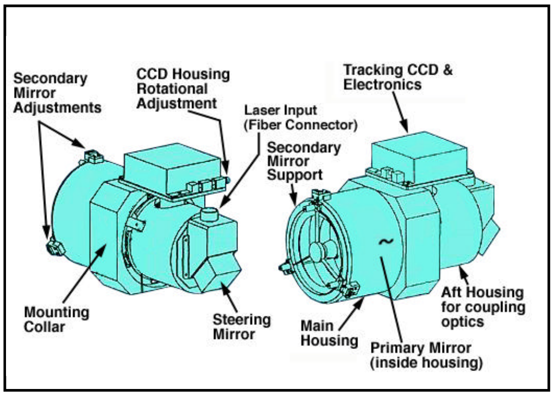

Figure 3.1.1 Optical Communications Demonstrator (OCD)

The OCD is currently under engineering model development; a flight model could be available for an NMP flight in late 1997. Estimates of the complete system mass, power, and volume (excluding the coarse-pointing gimbal) are 8 kg, 22 W, and 4700 cc, respectively. However, recent discussions with several advanced optics companies suggest that the mass could be further reduced. Consequently, a potential industry partnering relationship is currently being explored to bring this and other developments into the NMP Communications Systems IPDT.

3.2 Near-Earth

The deep space optical communications terminal just described is equally suited to near-Earth applications. However, the considerably reduced range of Earth-orbiting satellites allows data rates in excess of 1 Gbps to be supported from Geo.-to-ground (1-m stations) This terminal can also be used for inter-satellite links.
A second optical communications terminal has also been developed at JPL that offers a 0.5 Gbps capability at a lower mass (<5 kg), power (15 W), and volume (3375 cc). This terminal, SCOPE II, is a derivative of a small breadboard terminal developed as an experiment for possible flight on NASA's Cassini spacecraft (see Figure 3.2.1).

Figure 3.2.1 Small Optical Communications Spacecraft Terminal

The SCOPE II has a 1-cm aperture and a 300-mW semiconductor laser. The intended receiving station is configured around an autonomous, 1-m class tracking telescope. This terminal is suitable for Landsat 7 equivalent 150 Mbps data links, and can be configured to operate at commercial standard rates, e.g., 155 and 622 Mbps for low-Earth orbiter links. Both the SCOPE II and OCD terminals require gimbals for pointing and uplink optical beacons for acquisition and tracking, with powers of <1W and <10W, respectively.

Figure 3.2.2 shows a comparison for several optical terminals in terms of a bps/W metric (for the same range and receive aperture); the performance data shown was collected from open literature. As can be seen from this figure, both JPL terminals have good performances; similar good performances are also the case for these terminals in terms of bps/kg. However, it is noted that these metrics are projected from laboratory measurements and analyses. An NMP flight would demonstrate the actual performance.

3.3 Ground Tracking

Ground tracking of optical spacecraft requires the deployment of a network of stations, similar in concept to NASA's RF Deep Space Network. Site (spatial) diversity is essential to overcome the adverse effects of clouds and rain. Recent studies of ground station requirements indicate that 1-m and 10-m apertures are sufficient for near-Earth and deep space applications, respectively, as mentioned above. It is envisioned that optical communication systems will coexist with RF capabilities, particularly given the very large RF investment, and that a combination of both approaches will offer significant advantages to NASA and other users, e.g., commercial.

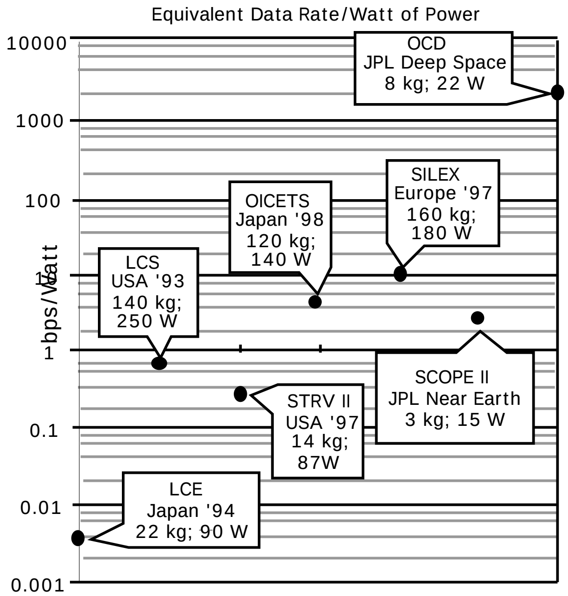

Figure 3.2.2 Optical Communications Terminal Comparisons

4. Short-Range Communications

From constellations of miniature spacecraft to robotic landers and planetary surface penetrators, the demonstration of revolutionary technology is key to the success of future space exploration. As the trend continues to reduce the size and mass of future scientific spacecraft, potential capabilities of these small spacecraft increase tremendously. With the advent of micromachining technologies, ultra-miniature communications systems are now becoming quite possible. Microelectromechanical systems (MEMS) are widely gaining acceptance as an enabling technology for numerous applications, e.g., sensors, actuators, imagers, accelerometers, and communications. By utilizing batch fabrication through planar IC processing, it is possible to fabricate a multitude of micromechanical components as easily as fabricating a single one. Combined with microelectronic devices, completely monolithic, micron-scale components and systems can be achieved. Advances in this processing technology will lead to more robust, lower cost systems. The University of Michigan’s Center for Integrated Sensors and Circuits, well known for their capabilities in micromachining technologies for sensors and signal processors, has been investigating single chip UHF to S-band wireless transceivers to meet the NMP’s goals of low mass, low cost, and low power consuming communications systems.

Many present strategies for achieving single chip heterodyne transceivers currently implement high-Q RF and IF components in SAW, quartz, or ceramic resonator technologies. Circuit complexity and high levels of system integration add to the problem of multi-chip designs. Micron-scale, high-Q, on-chip mechanical resonators can be fabricated using capacitively or piezoelectrically transduced approaches, thus relieving the need for high levels of systems integration. A MEMS resonator can offer orders of magnitude reductions in size over comparable SAW designs (see Figure 4.1).

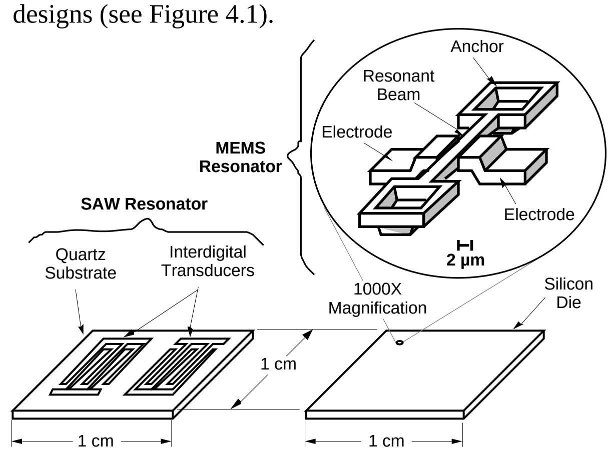

Figure 4.1: Size Çomparison of SAW vs. MEMS Resonator

Reducing the circuit complexity by combining functions on a single chip will also decrease the susceptibility to radiation in space applications. Passive components such as RF bandpass and image reject filters, and oscillators, are inherently replaceable via the MEMS approach. Among the components specifically being investigated for NMP are RF filters ranging from 800 MHz to 4 GHz; IF filters in the 455 kHz to 254 MHz range; and highly stable UHF local oscillators. Table 4.1 compares SAW vs. MEMS implementations for an IF bandpass filter at a center frequency of 254 MHz, with 400 kHz bandwidth.

Parameter	SAW (state-of-practice)	MEMS (Projected)	Improvement Factor
Quality Factor (Q)	~40,000 (resonator)	40,000	- -
Insertion Loss (dB)	~ 7	< 0.5	4
Area (mm^2)	10^2	$2.5x10^{-3}$	40,000
Mass (kg)	10^{-3}	10^{-12}	10^9
Q/kg	$4x10^7$	$4x10^{16}$	10^9

Table 4.1: SAW vs. MEMS Filter Comparison

The current CMOS MEMS fabrication technology at the University of Michigan is limited to transition frequencies, f_T (gain-bandwidth product) of about 300 MHz. By integrating MEMS into higher frequency fabrication processes (SiGe or GaAs), f_T can be extended to much higher frequencies.

Beyond space exploration, MEMS technology can offer vast terrestrial commercial spin-off potential as well. Cellular phones and wireless LANs are just a few commercial areas in which this technology can greatly contribute.

5. Summary

NASA's vision of space exploration in the 21st century is predicated on the development of small, highly autonomous spacecraft. The New Millennium Program has been established to develop and validate new and innovative spacecraft technologies to meet this vision. Advance communications technologies and systems have been identified that will substantially reduce the telecom impact on spacecraft, while, in many cases, providing improved performance.

Acknowledgments

The authors wish to thank the industry/academia members of the IPDT for their efforts: Tom Blakney, from Boeing; Larry Newman, Lockheed Martin; Rol Chapman, Space Systems/Loral; Mickey Haney, TRW; and Clark Nguyen, Univ. of Michigan. Thanks also go to many engineers at the Jet Propulsion Laboratory, including Lance Riley, Jim Lesh, Marty Herman, and Richard Horttor; the Lewis Research Center, especially Jim Dayton and Ron Bexten; and the Goddard Space Flight Center, particularly Warner Miller, Mike Krainak, Dave Zillig, and Bob Jones, for their contributions and energy.

The work described in this paper was carried out at the Jet Propulsion Laboratory of the California Institute of Technology under a contract with the National Aeronautics and Space Administration.

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